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ORBITAL SERVICING: ISSUE OR ANSWER?

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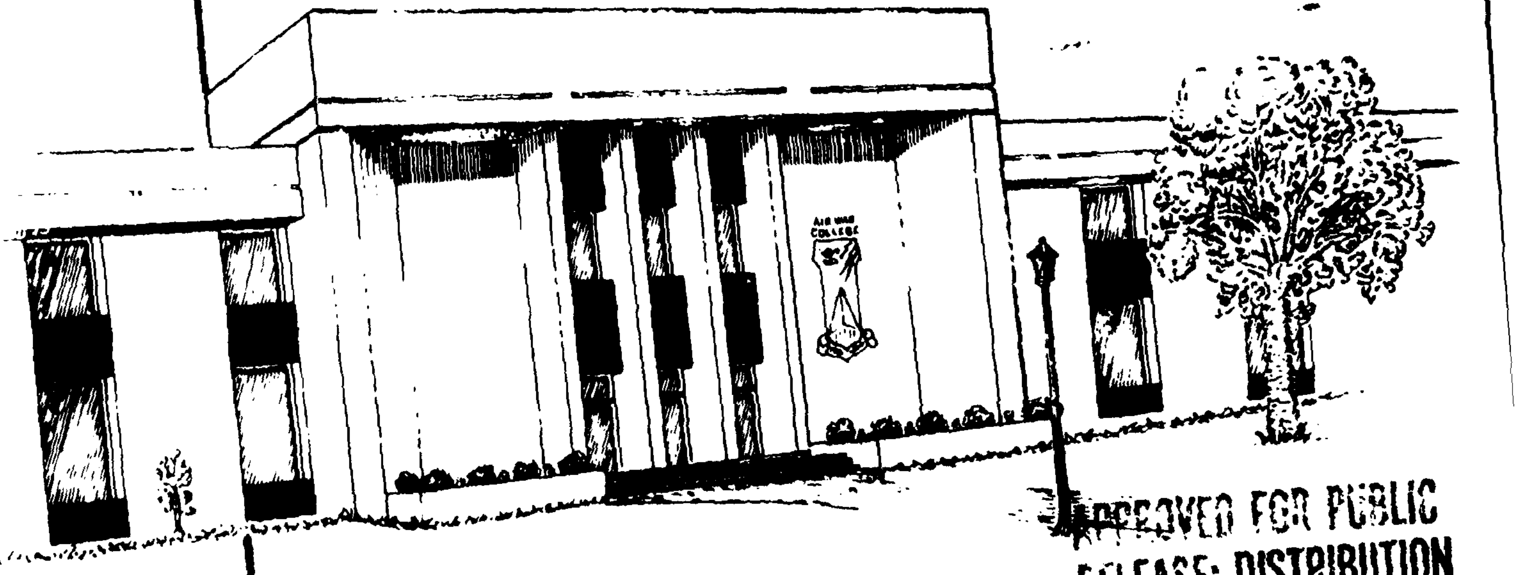

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ORBITAL SERVICING: ISSUE OR ANSWER?

by

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EXECUTIVE SUMMARY

TITLE: Orbital Servicing: Issue or Answer?

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Reviews on-orbit satellite servicing as a forward-based logistic concept through an examination of its potential military benefits to endurance and survivability of space systems. Analyzes reasons for opposition to implementation of the program within the military space environment by focusing on the orbital refueling subfunction. Assesses the potential of orbital servicing to increase system capability and survivability while reducing system costs.

BIOGRAPHICAL SKETCH

Lieutenant Colonel Douglas P. Hotard (M.S., Engineering, Stanford University) has been involved in the U.S. military space program since his assignment to the Air Force Satellite Control Facility in Sunnyvale, California in 1980. An electronic systems specialist, he has experience in radar, satellite command and control, data processing, and systems development. He is a graduate of the Armed Forces Staff College and the National Security Management Course, where his papers on artificial intelligence applications to space systems received outstanding ratings. Lieutenant Colonel Hotard is a graduate of the Air War College, class of 1989.

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CHAPTER I

INTRODUCTION

On-orbit satellite servicing is a much discussed and controversial issue within the American space operations and development community. Its history is marked by continuing arguments over its economic feasibility and the contributions it can make to our military capability in space. On-orbit servicing was originally conceived as part of an optimistic plan to use the Space Transportation System (STS) to deploy and sustain a considerable space station-based manned presence in space. As a maintenance concept which would enable orbital recovery, repair, and refit of malfunctioning or aging satellites, on-orbit servicing promised a future where space system life cycle costs could be reduced by extending the useful life of these expensive assets. Because satellites would have much longer endurance, requirements for replacement satellites would be reduced and fewer launches would be needed to maintain the system. Through the projected advantages of space-based logistics, on-orbit servicing would make space systems much more cost-effective.

The cost argument for space logistics began to lose credibility concurrent with the STS's failure to

deliver on promised reductions in space launch costs. Additionally, the grounding of the shuttle for 32 months after the Challenger disaster brought into sharp focus the vulnerability of a space support concept based on a single manned launch vehicle. As a result, on-orbit servicing has undergone a major reevaluation, particularly in the context of its military application.

In addition to the cost questions of on-orbit servicing, the issue of space system survivability was gaining attention as senior leaders perceived our dependence on space assets increasing dramatically for a wide spectrum of military activity (8:46). Expanding beyond the traditional role of surveillance and warning, space-based "force multipliers" are now achieving a routine but essential status in our peacetime environment. The NAVSTAR Global Positioning System (GPS) navigational satellite system; the Defense Meteorological Satellite Program (DMSP); world-wide communications through satellite relay (MILSTAR, DSCS, FLTSATCOM); and near-real-time intelligence and surveillance systems have all become embedded into the daily U.S. command, control, communications and intelligence (C3I) infrastructure. Because these space systems are highly effective and reliable during peacetime, our dependence on them becomes a vulnerability for our C3I capability if their

availability is not ensured during war. As Lt. General Leo Marquez said in 1985, "A force multiplier is a force divider if it is lost in combat."

To have true military utility, on-orbit servicing must provide benefits across the entire conflict spectrum. For a variety of reasons, the concept has not yet developed into a viable program which preserves and enhances our war fighting capability. This paper will analyze the major issues surrounding on-orbit servicing, examine why it has not been implemented in the military space operations environment, and assess whether this concept still offers military advantages in the following key areas: increasing space system capabilities, reducing overall costs, and enhancing system survivability.

CHAPTER II

THE NEED FOR SPACE SYSTEM SURVIVABILITY AND ENDURANCE

In the President's national space policy announcement on March 23, 1983, he established the direction of the national space effort over the next decade (1:A-1). One of the significant issues included in the national security section was concern over the survivability and endurance of space systems which are required for use in crisis and conflict. Recognizing the increasing reliance that this country has placed on space systems to increase its national security, the President directed that deficiencies in space system survivability would be identified and eliminated through an aggressive, long-term program. The objective of this program would be to ensure the availability of crucial space systems over a wide range of potential conflict situations.

Endurance for Peacetime

Satellite systems are now the United States' primary source of information about economic and military developments in the Soviet Union (39:1). The challenge in the upcoming decades will be to maintain the effectiveness of these systems while controlling their costs in an environment of deficit-driven budgetary constraints and

tightened military spending. Increasing the endurance of satellites during peacetime implies cost advantages because replacements will not be needed as often, so additional hardware and launch costs are avoided.

To an extent, this has been the objective of an on going effort for years. United States military satellites are designed for long lifetimes through high quality components and built-in redundancy (21:170). However, during normal operations failures in components of on-board subsystems are inevitable. As these satellite performance anomalies are detected, redundant units are switched in to continue the operation of the satellite. Unfortunately, if critical subsystems fail completely the entire satellite must be replaced. This requires spares, either on-orbit or on the ground ready to be launched, in order to minimize mission interruption. This sparing concept has the effect of making the entire satellite the minimum replaceable unit (16:17). With satellites costing as much as $300 million or more, this type of sparing is increasingly difficult in times of huge budget deficits and zero-growth defense budgets.

Survivability During Wartime

The concept of space assets as wartime command, control, communication and intelligence force multipliers

is not yet fully woven into the fabric of war fighting doctrine (10:132). One obstacle to effectively incorporating space systems into appropriate doctrine is the continuing concern over the survivability of these systems. To effectively support combat, space missions must be able "to survive appropriate threats for as long as they are needed" (2:327). The level of reliance that military commanders put on space to support theater operations plans will probably be directly related to the war fighting value and dependability of the satellite system. As a result, space's ultimate contribution to war fighting will depend largely on survivability technologies (39:12).

In the effort to balance cost control with improvements in satellite endurance and survivability, one compelling approach is to incorporate peacetime endurance improvements which also enhance wartime survivability. On-orbit servicing may offer this type of synergy. Originally intended as a means to increase the on-orbit lifetimes of our space systems, on-orbit servicing may also offer the potential for significant survivability advantages. To explore these advantages and to aid in analyzing on-orbit servicing in general, this paper focuses on the process of on-orbit refueling. Refueling is a basic building block of on-orbit servicing and is

common to most studies of space-based logistics. This paper next examines on-orbit refueling as a forward-based logistics concept, reviews its advantages and disadvantages, and analyzes why it is not yet integrated into our military space operations.

CHAPTER III

THE CONCEPT OF FORWARD BASED SERVICING

The Army, Navy and air-breathing Air Force have long ago proven the benefits of forward-based resupply. An important common denominator in the services' combat logistics principles is refueling. For example, all first-line Air Force fighter aircraft are designed for aerial refueling. This allows more of the aircraft weight to be used for offensive and defensive subsystems which increase its overall capability and survivability. Refueling tankers allow the fighter aircraft to have the smallest on-board fuel tank possible within its operational requirements, while allowing lighter weight, better design, more offensive and defensive systems, and enhanced combat radius, loiter time and range. Given the range requirements of modern fighters, their designs without the existence of aerial refueling capability would be radically different.

The Navy recognizes the value of forward logistics through underway replenishment. Carrier battle groups do not return to port for replenishment when they run low of consumables. During a conflict, prepositioned stocks and resupply ships bring the replenishment function directly to the combat arena.

The Army also recognizes the value of the flow of supplies to the front as noted in FM 63-3 (26:1.4), which emphasizes the importance of stocking critical supplies near points of anticipated consumption in order to permit continuous operations. The combat mobility of the forward units is the crucial issue.

In each of the services' doctrine and employment plans, forward-based logistic functions increase the combat capability of the units being supported, thereby increasing their combat survivability and reducing losses. The effect is to reduce the overall cost for an increment of combat capability. This concept is well understood -- no one wants to design an army tank which carries all of its required fuel for a prolonged conventional war. That would be equivalent to designing an automobile which would have 75,000 miles worth of gas in it when it is purchased. The reality of gas stations makes that idea absurd. But, as this paper is written, the designs for all military satellites include launching along with the payload all the necessary fuel for the entire lifetime of the satellite. Since the trend in this country is to build more sophisticated satellites with longer lifetimes, the amount of fuel needed will steadily increase.

CHAPTER IV

ON-ORBIT SERVICING AS FORWARD BASED LOGISTICS SUPPORT

In its broadest sense, on-orbit servicing of space systems is an extension of the logistics support concept from the ground to space. On-orbit servicing can encompass a wide variety of logistic activities; primary among these are:

- resupply of consumable propellants and cryogenics
- replacement of failed components
- technology upgrades
- preventive maintenance
- transportation to different orbits.

These functions can be either ground controlled or space station/space shuttle controlled; manned or unmanned; automated, telerobotic or manual. The intent of the servicing is to increase the effective lifetime and utility of the satellite mission.

To understand satellite logistics is simple once one has a basic understanding of satellites. The reason for the existence of the satellite is its payload. Apart from orbital weapons, military satellites are usually designed to collect, relay, store, or transmit data of national security importance. The payload is generally a

sensor or a receiver-transmitter which is intended to effectively perform a limited number of functions. Some satellites carry more than one payload; for example, a navigation satellite might also have a communications relay payload. The remainder of the satellite subsystems exist to support the operation of the payload. Briefly, those systems are:

- attitude control
- power generation and storage
- environmental control
- communications
- propulsion (Fig. 1).

On-orbit servicing can involve all satellite subsystems, but the most interesting is the refueling activity. Although satellite missions and payloads vary widely, they all have one common requirement -- the need for fuel. Fuel is used in the reaction control propulsion system to accomplish various attitude changes, velocity corrections and station-keeping maneuvers which are vital to the proper functioning of the satellite. Low orbit satellites (100-400 miles) must frequently expend fuel to counteract the forces of atmospheric drag and to control vehicle attitude. Satellites at higher altitudes face smaller drag problems, but must contend with orbital

perturbations caused by third body gravitational effects, the oblateness of the earth, and solar winds (34:2-41). Given perfect performance of all other on-board subsystems, all satellites will ultimately run out of fuel, which will result in their demise as useful platforms. The universal criticality of fuel makes the refueling function the fundamental on-orbit servicing operation.

Potential Benefits Exist

On-orbit fuel servicing is usually described as refueling of a spacecraft while it is still in orbit. In the simplest case, an orbiting refueling vehicle would move into position, dock, and transfer propellants to the customer satellite. It would then decouple and proceed to its next assignment. An orbiting refueling vehicle may be used to periodically service the space vehicle throughout its mission life. The immediate advantages of such a system are the decreases in initial launch weight of the customer vehicle due to the lower propellant fraction required. Launch weights are a major determinant of launch costs. Since propellant fractions (ratio of fuel weight to total weignt) can vary from 30 to 90 percent, significant weight savings can be theoretically achieved. Instead of launching a vehicle with its entire lifetime

supply of fuel on-board, it is possible to include only a prudent fraction of that amount, assuming the guaranteed availability of on-orbit fuel resupply as required. The Air Force has determined that "many satellites whose life is governed by the life of the embedded propulsion system could now have extended life if the propulsion system could be resupplied." (20:A-4).

In 1984, then Air Force Vice Chief of Staff Larry Welch directed the Air Force to pursue and apply on-orbit maintenance options for all new programs, and for future block changes to existing programs where these options might be prudent (27:1). Each space system would be analyzed for the cost-to-benefit balance of spacecraft servicing, depending on several factors:

- the age and complexity of the system
- the criticality of the spacecraft to national security
- spacecraft replacement cost
- availability of new technology which could improve the performance of a replacement spacecraft
- the added life expectancy or capability to be realized from servicing actions (29:17).

Despite what appear to be obvious advantages to on-orbit servicing over the existing arrangement of launching each satellite complete with a lifetime fuel supply, the arguments against on-orbit servicing have been strong enough to delay establishing a coordinated program.

The Program Has Not Been Developed

One reason for the delay is the guidance developed to implement the 1984 policy. A crucial directive which was passed down to system program directors was that the applicability of on-orbit servicing was to be assessed on a program-specific basis. This had the effect of compartmentalizing the costs of beginning the initiative to individual programs and their program directors. As a result, the lack of individual program advocacy for on-orbit servicing is not surprising, since the first program director to volunteer would be shouldering the entire development cost and risk.

To be sufficiently comprehensive, the results of an analysis of on-orbit servicing must be made in the context of the entire military space system. An overall assessment of on-orbit servicing should not only address the appropriateness of each program's participation, but must factor in ground support, launch, command, control, communication, training and architecture issues which

cross program boundaries and *overlay* the entire military space effort. In this wider context, on-orbit refueling has an analog in the historical development of aerial refueling.

The fact is that on-orbit servicing has not yet been integrated into military space operations due to continued resistance to the concept. The *rationale* in opposition to on-orbit servicing condenses into a handful of issues:

- individual program risk
- efficacy of survivability enhancements
- orbital maneuver problems
- launch and support costs.

Each of these objections will be presented and analyzed to determine if existing or emerging technology or changing cognitive perceptions can alter the negative attitudes that prevail. The analysis will be done in the context of the contributions on-orbit refueling can make to reducing space system costs and increasing total space system capability and survivability.

CHAPTER V

PROGRAM DEVELOPMENT RISK

In developing military satellite systems, the system program director is faced with extraordinary challenges. He must develop, test, and deploy expensive, highly complicated launch/ground/space systems which must pass stringent cost-benefit analyses made in the context of national security. With probable continuing pressure in the foreseeable future to reduce overall defense budget increases, the program director must carefully balance the potential national security enhancements of military systems with the overall costs of the program. Expensive systems receive a high-degree of public and congressional scrutiny, with the most technologically ambitious, and therefore risky, programs getting the most attention. The continuing national debate over the deployment of the SDI ballistic missile defense system is a case in point. The polarity in the arguments between opponents and proponents of this system can be attributed to differing perceptions over the basic cost/benefit relationship. The depth of disagreement comes from many factors, but a primary one is that both sides of the equation -- cost and benefit --

are filled with risk. There is uncertainty as to the cost of the program and uncertainty as to how well it actually will enhance national security.

The example of SDI risk assessment has an analog in every space program: space system development and employment is inherently risky. In an era in which he must compete for dollars not only among other military programs, but also between military and non-military budgets, the program director must minimize cost for a given military capability objective. And in program management experience, managing cost means managing risk.

Propellant Management

It is in this risk management context that we can characterize one component of the reluctance of program directors to enthusiastically embrace on-orbit servicing for their space systems. The risks can be categorized as both technical and operational First, is the on-orbit servicing system feasible? Second, is it practical (15:5)? No program director will ever launch a multi-hundred million dollar satellite without assurance of adequate fuel. Propulsion is a mission essential subsystem in any satellite and is indispensable in achieving and maintaining correct orbital position upon which the mission performance of the payload is always

dependent. The propellant requirement is so important that it is one of the major determinants of system design. For a given launch weight, very high propellent fractions can only be achieved by reducing the weight of all other components, including the payload (28:37).

Failure to properly plan for fuel budgets can be catastrophic. The unscheduled de-orbit of the U.S. Skylab in 1979 was due in large part to a lack of propulsion to counteract unexpected atmospheric drag in its low earth orbit. In fact, one recent study shows propulsion system failure to be the second leading cause of spacecraft anomalies, accounting for 25 percent of all satellite subsystem failures (30:15-20). As a current example, the Solar Maximum satellite, repaired by a shuttle mission in 1984, is projected to de-orbit and be destroyed on re-entry by early 1990 due to an exhaustion of its fuel supply (41:36). With empirical evidence like this, the sensitivity of system program directors to fuel issues is understandable. But if design constraints on payloads and other subsystems could be softened by an easing of the propellant burden, serious attention to on-orbit refueling should make sense.

The Soviets proved the feasibility of on-orbit refueling with their Salyut space station (18:27). They developed automatic docking in 1978, and since 1980 they

have transferred fuel to the Salyut space station automatically from unmanned Progress tankers. The Soviets have become very proficient at consumables resupply, and there have been no reported accidents during docking or transfer (29:48). Various studies in the U.S. have also indicated a high degree of optimism that technical risks associated with propellant transfer in space are minimal (20:B-13). Reviews of available technology and projected near-term developments reveal that the primary category of risks were mainly concerned with inadvertent fluid spills and resulting fire or corrosion hazards to vehicle components (18:27).

Since even moderate complexity associated with proven or similar technology can push cost growth to 1.5 to 2.0 times estimates (31:63), the military satellite developer would prefer to have technical practicality demonstrated prior to incorporating new designs into mission essential systems. He is willing to pay higher launch costs due to more on-board fuel weight in order to avoid the risk of new refueling capabilities. Despite military reluctance in the matter, the process of developing space logistics technology continues. Through the political decision-making framework of the national space program, the risk of on-orbit servicing development has fallen upon NASA.

The NASA Orbital Maneuvering Vehicle

The NASA Orbital Maneuvering Vehicle (OMV) is a remotely controlled, reusable, free-flying space vehicle which is projected as an integral part of the future STS system (40:1). Scheduled to be operational in the mid-1990's, the OMV is being designed to perform a wide range of on-orbit services in support of orbiting spacecraft. Among its many potential uses, the OMV is capable of spacecraft retrieval from orbits above the base facility (either the shuttle or the space station), payload delivery to higher orbits, remote servicing, and module exchange. Its initial operations will be at low-earth orbit. Its capability for altitude changes is limited for large payload transfers (Fig. 2). For longer-range support, such as to geosynchronous altitude, another vehicle called the Orbital Transfer Vehicle (OTV) will be required (16:18).

It is NASA's view that the resupply of spacecraft fluids and the exchange of orbital replacement units on spacecraft has great economic benefits (33). Studies developed by supporting contractors analyzed the ability of the OMV to provide servicing functions in three designs:

- As a stand-alone resupply vehicle
- As a resupply vehicle with a large volume tank
- As a resupply vehicle with module exchange kit.

The results of the studies strongly suggest that the basic OMV will be suitable as a propellant resupply vehicle, but that the additional large volume task is necessary to allow a cost-effective mission profile (33). Although there are several technical issues to be overcome, the forecast is optimistic. One key technology of this system -- the ability to transfer fluids in a zero-gravity environment -- was successfully demonstrated by the orbital resupply system experiment on Space Shuttle Flight 41C in 1984 (33). NASA has also tested new quick-disconnects and sensors required for successful docking.

One issue with the OMV/tanker concept is the upper limit of launch payload capability for deployment of the OMV carrying a large tanker module (33). The utility of the OMV as a refueler will increase with the amount of fuel which it transfers and the number of vehicles it can service. It is currently projected to have a 9,000 pound fuel transfer capacity. As the tank becomes larger, the

weight becomes a critical factor for launch costs, as will be discussed later. Also, as the tank becomes heavier, the OMV's ability to maneuver to different altitudes and its ability to change orbital inclinations are increasingly constrained (Fig. 2). These limitations have important consequences for the operational success of the on-orbit servicing concept. But NASA, through its OMV and associated follow-on programs, is eliminating many, if not all, of the technical risks associated with orbital refueling. The operational and cost issues are still on the table.

Operational Risk

Once the technological risk is reduced to manageable levels, the question of operational risk becomes foremost in the program director's mind. If a satellite system is designed for minimal embedded fuel storage, it becomes highly dependent on the owner/operator of the refueling service. If the servicing function has a "common-user" architecture, then propellant management and refueling demands may be subject to a volatile, centralized priority system. This in itself could be a vulnerability. An analogy can be drawn here with the competing demands made by tactical and strategic aircraft on KC-135 and KC-10 refueling resources during wartime.

But, as will be discussed later, there are other reasons why an on-orbit refueling system should be tied to a single program, or at most to a limited number of similar programs. In this way, the program director does not have to fear loss of his satellite due to a confusion of priorities.

Thus far, this review of the military reluctance to embrace the concept of on-orbit servicing reveals the NASA OMV to be a crucial program. If it is successful, technology transfusion can directly benefit the military space community. Much of the technical risk of satellite servicing will have been overcome. If military test programs are initiated, sufficiently foresighted management of the space logistics support network should be able to solve the operational problems as well. Once the feasibility and practicality of on-orbit servicing are demonstrated, the next area of bias to be addressed is military utility. Can on-orbit servicing help make our warfighting satellites survivable?

CHAPTER VI

THE SURVIVABILITY ARGUMENT

A discussion of space system survivability must include the vulnerabilities of the space system, the threat, and possible countermeasures. A space system can be defeated by neutralizing any one of its three main components: the space segment, the ground segment, or the communications link between the two (25:25). This analysis will concentrate on the vulnerability of the space segment to direct attack. The survivability of a satellite hinges upon whether a defense can make attacking the satellite too costly for the attacker, or whether the offense can make defending the satellite too costly for the defender (7:14).

The Threat to Military Satellites

Known or probable anti-satellite threats include (24:2, 25:28):

- ground-based directed-energy weapons
- spaced-based directed-energy weapons
- conventional, co-orbital, radar-guided ASAT
- conventional, co-orbital, electro-optically guided ASAT

- nuclear, direct-ascent, inertially-guided ASAT
- space mines.

The variety of potential direct threats to satellites preclude the 100 percent effectiveness of any single survivability measure, but the vulnerability of the orbital segment can be reduced by efforts in three areas:

- precautionary measures which make ASAT attacks more difficult
- defensive measures that allow the satellite to avoid or survive an attack
- redundancy measures to maintain satellite function upon the loss of primary subsystems (6:78).

Precautionary measures include positioning satellites out of range of ASAT threats and using "stealth" technology for low visibility and reduced radar cross sections and other detection parameters. Defensive techniques include evasive maneuvering, attack warning devices, decoys, shoot-back, and shielding or hardening against nuclear EMP and directed-energy weapons (6:80). Redundancy measures include on-board spare components,

on-orbit spare satellites, robust launch capability for replacement, and back-up airborne and ground systems (4:x). Our primary concern is to deny the enemy an easy "quick kill" option which would seriously damage our space-based warfighting systems (4:35). The Soviet Union's co-orbital anti-satellite system was first tested in 1967 and has been operational for over 20 years. Possessing a large number of ASAT launch vehicles, the Soviet co-orbital ASAT presents a realistic threat to U.S. satellites in low-earth orbit (32:79).

Evasive Maneuver As a Defensive Measure

The most potentially effective survivability measure against the near-term ground-based, co-orbital ASAT threat is evasive maneuver (6:78). Traditionally, our satellites were viewed as basically positional forces, designed to perform important tasks in peacetime, and to warn of the imminence of war. It was not originally a major criteria that they be survivable. As a result, many are large, heavy, hard to protect, and very expensive (5:53). Their location in space is predictable and they can be attacked. But evasive action used in conjunction with attack sensors and stored on-board instructions for auto-maneuvering should severely complicate the ASAT problem. The key issue in evasive action as a

survivability measure is fuel -- orbital maneuvering can be extremely costly in terms of fuel. This is a case where on-orbit refueling can make a survivability difference. The availability of an orbital refueling vehicle can result in the following advantages:

- smaller overall satellite size and radar cross section due to smaller on-board fuel tank
- more aggressive maneuverability due to smaller mass
- for a given vehicle weight and size, more on-board defensive systems made possible by smaller propellant fraction
- for a given vehicle weight and size, more redundant subsystems made possible by smaller propellant fraction
- for a given sized booster, more capability can be launched with near dry tanks.

Maneuverability is so potentially important to survivability that it reportedly has been incorporated as a defensive measure on certain large satellites without fuel replenishment capability (3:25). Maneuverability is also obviously effective in repositioning satellites for more flexibility in mission objectives.

There are drawbacks to the use of evasive maneuvers. The great use of fuel which accompanies emergency evasive maneuvering can itself be fatal to the system. If the evasion of an ASAT attack results in a total depletion of remaining fuel, the ASAT attack was successful. Additionally, the mission of the satellite is effectively interrupted during any emergency maneuver as rapid orbital changes usually disrupt the payload function and require some reconfiguration of torque-sensitive components, such as solar panels or large antennas. The design of a rapid maneuvering propulsion system must also be incorporated into every vehicle. In addition to these factors, maneuverability is not particularly effective against directed-energy weapons or covert space mines (24:xiv).

There also exists a valid argument that an orbiting refueler constitutes yet another critical node in the space architecture, itself a target. But since the refueler would be inherently a maneuvering vehicle, all survivability advantages accruing to evasive maneuvers would be applicable to it as well.

The synergistic effects of the maneuver-refuel combination on survivability and endurance have not overcome the realities of program management decision-making. The fact remains that no U.S. satellite

has yet been attacked by an ASAT. So, when faced by the inevitable payload weight, cost, or size overruns, the program director's first cuts are usually in survivability subsystems (9:66). But this does not have to be the case forever. If an orbital refueling capability existed, spacecraft design for defensive subsystems, redundancy, size, and weight would be given new latitude and flexibility. The resulting changes could improve space system capability and survivability.

CHAPTER VII

THE ORBITAL MOBILITY PROBLEM

One of the original justifications for the space transportation system was its potential for supporting the repair or recovery of failed spacecraft (33:2-5). The STS demonstrated this capability numerous times, the most well-known being the retrieval and on-orbit repair of the Solar Maximum and Leasat satellites in 1984 which, by some estimates, saved almost $300 million (14:13). The limiting factor with STS, space station, OMV, or OTV orbital servicing is in the inherent physical problem of changing orbital planes. Newtonian physics dictate that the space vehicle is going to revolve around the earth in an elliptical orbit on a plane that passes through the center of the earth and the vehicle (34:2-24). To achieve orbit at an altitude of 100 miles, the space vehicle must be traveling at approximately 17,500 miles per hour (35:40). In fact, all satellites are moving very fast, even the "stationary" ones at geosynchronous altitude (22,300 miles), which move at approximately 7,000 miles per hour to match the rotation of the earth. To change altitude (to move to a higher or lower orbit) or to change inclination requires a change in velocity, or delta V, which is provided by rocket engines burning propellants.

The amount of propellant required for a particular orbital maneuver is determined by a number of equations (34:2-37), which reveal that in terms of fuel, changing altitude is somewhat expensive, but changing orbital inclinations is enormously expensive (Fig. 3).

Since one major advantage of an on-orbit servicing capability would be its versatility in refueling a variety of satellites, the issue of orbital mobility is extremely important. In order to dock with a customer satellite, the servicer must be in the same orbital plane, at the same orbital position, and moving in the same direction. The process is similar to an F-15 refueling from a KC-10, except that in space it is the refueling vehicle which must use fuel in order to maneuver itself into refueling position.

In examining the versatility of the on-orbit refueling concept, serious attention must be given to the capacity of the refueler and its range of orbital mobility. Military satellites of strategic national importance are in many different orbits at many different altitudes (Fig. 4). Reconnaissance satellites are generally in low-earth orbit, between 300 and 500 miles, with high inclinations in order to get daily earth coverage. Navigational satellites such as GPS are at 11,000 miles in a variety of planes. Surveillance and

communications satellites can be located at geosynchronous altitude in circular orbit, or in a variety of highly elliptical orbits with greatly differing apogees and perigees. The number of U.S. military satellites in orbit varies from 40 to 65 at any one time. The challenge to a single refueler to service this array of customer satellites is staggering. For instance, NASA estimates that the amount of fuel required for moving a 6,000 pound satellite from a 98 degree to a 28.5 degree plane is approximately 70,000 pounds of high impulse propellent (36). At this point, 70,000 pounds is more weight than the U.S. can currently launch into space on a single launch vehicle (37:192). Because of the huge fuel cost of orbital inclination changes, NASA's OMV will be restricted to providing services at planes very close to its initial launch inclination. So it is farfetched to plan on a single or even a small number of refueling satellites to service the entire military constellation. Offsetting this finding are the following observations:

- Refueling vehicles can be designed for servicing at specific orbital planes, such as geosynchronous or polar.
- Specific multi-vehicle programs with more than one satellite at the same orbital inclination can be given dedicated service.

- Plans for future programs can factor in the on-orbit refueling capability to optimize orbits for constellation service.
- Refueling vehicles may be launched on demand into the precise orbit as required.
- The physics of orbital transfer may allow servicing of constellations in nearly identical inclinations, although longer transfer times may be required.
- Mission analysis may determine that certain types of satellites do not require the refueling capability.

The ultimate design of an efficient on-orbit servicing architecture can be one that crosses program lines, such as between the DSCS and FLTSATCOM constellations at geosynchronous orbit. There consequently exists a requirement to design standardized docking interfaces, fuel combinations, and telemetry streams to allow for common activities with the servicer. The cost implications of this standardization are not clear (22, 23). Once again, the Air Force policy direction to review on-orbit servicing on a program-specific basis may interfere with the achievement of an overall system "best" solution.

CHAPTER VIII

LAUNCH AND SUPPORT COSTS

The options considered by system planners for reconstitution of failed satellites will always include satellite replacement. As mentioned previously, this is now the standard procedure for military satellites. One of the determining factors in the choice between implementing on-orbit servicing or continuing with satellite replacement is likely to be launch costs, a fundamental determinant of all space system costs. Launch costs vary directly with payload-weight-to-orbit (Fig. 5). The standard measurement used in launch system calculations is cost-per-pound-to-orbit. Shuttle launches cost approximately $5,000 per pound (17:2), while expendable launch vehicle costs range from $3,000 to $4,000 per pound (16:18). As technologies for robotics and artificial intelligence mature, their use in space will reduce the need for expensive manned launch services to support on-orbit military applications (12, 13:45). While trying to reduce its dependence on the shuttle for heavy lift, the Air Force is determined to trim launch costs to an ultimate goal of one-tenth of today's costs (11:24). This objective, if it is ever achieved, will go a long way to reducing overall space system costs.

However, in the on-orbit servicing analysis, reduced launch costs must be considered in relation to other factors, such as:

- the number of launches required to deploy and sustain the servicing system
- the cost to develop, operate and maintain the ground support system for the servicers
- the development costs of adapting satellites to servicing and maneuver configurations
- the costs of more built-in satellite redundancy and defensive systems made possible by reduced fuel weight
- the cost of designing longer-life components required by extended satellite lifetimes.

For purposes of simplicity, this analysis focuses on refueling and does not address other on-orbit servicing functions. As a result, the intangible costs of technical obsolescence of satellite payloads should also be addressed. It is not clear that indefinitely extending the life of a satellite is desirable if technical progress makes the payload obsolete. However, advanced on-orbit maintenance operations such as module replacement could help solve this problem.

In a 1987 analysis of on-orbit repair, Air Force Space Division concluded that decreases in overall mission costs and potential gains in mission capabilities are possible if a combination of on-orbit servicing and spacecraft sub-system redundancy is implemented (38). Unfortunately, the analysis did not address the details of launch costs and the number of servicers required. To correct this, each satellite program, such as DMSP, GPS, DSCS, etc., must assess its optimum number of servicers. Then the military constellation must be analyzed in aggregate to explore the advantages of sharing servicers. The size (i.e., fuel capacity) of the servicers can then be determined and launch, operations and maintenance costs can then be estimated. At this point, the preceding analysis remains theoretical. It would seem obvious that there will be additional launch and hardware costs incurred at the onset of the effort, with costs savings to be realized in later years as satellite endurance begins to pay dividends (Fig. 6). Additionally, if increased survivability results from the on-orbit refueling program, the replacement costs saved on satellites not lost to hostile action must be factored in. All that can be stated for certain is that overall space system costs will

decrease if, for the entire constellation of servicers and customer satellites, launch cost savings offset any net increases in hardware and ground support costs.

CHAPTER IX

CONCLUSION

This assessment of on-orbit satellite refueling is made in terms of its ability to reduce system costs and increase both space system capability and survivability. According to available sources, there seems little doubt that average satellite mission life can be extended by eliminating the occurrence of fuel exhaustion. Weight saved by reduced on-board fuel storage can be converted into increased redundancy and embedded defensive systems which would enhance endurance, capability, and survivability. It is also apparent that the availability of refueling would permit ASAT avoidance maneuvering which increases the likelihood that a satellite will survive a direct attack. In terms of increasing endurance, capability, and survivability, on-orbit servicing appears to hold great promise. There are several converging trends which support the practical aspect of the concept:

- The high cost of manned spaceflight, coupled with continued advancements in technology, will move space system planners toward more automated orbital systems.

- The need for better arms control monitoring and better targeting data will probably lead to more satellites in the surveillance constellations (6:40). The more satellites in similar orbits, the more supportable the servicer argument becomes.
- The fiscal necessities of reducing overall military costs will mandate the adoption of cost saving measures.
- The practical demonstration of orbital servicing will be accomplished by NASA through its OMV program.
- The requirement for space system support to forces throughout the conflict spectrum will demand survivability upgrades.

The synergistic effects of on-orbit servicing are seen in its potential improvements to both endurance in peacetime and survivability during conflict. The major limitation to the concept lies in its vulnerability to the cost issue. Without reasonably firm knowledge of the scope of costs to be incurred across the entire military space program, a cogent argument on cost savings cannot be made. If launch costs eventually decrease past some critical point, the increase in cost for launches to

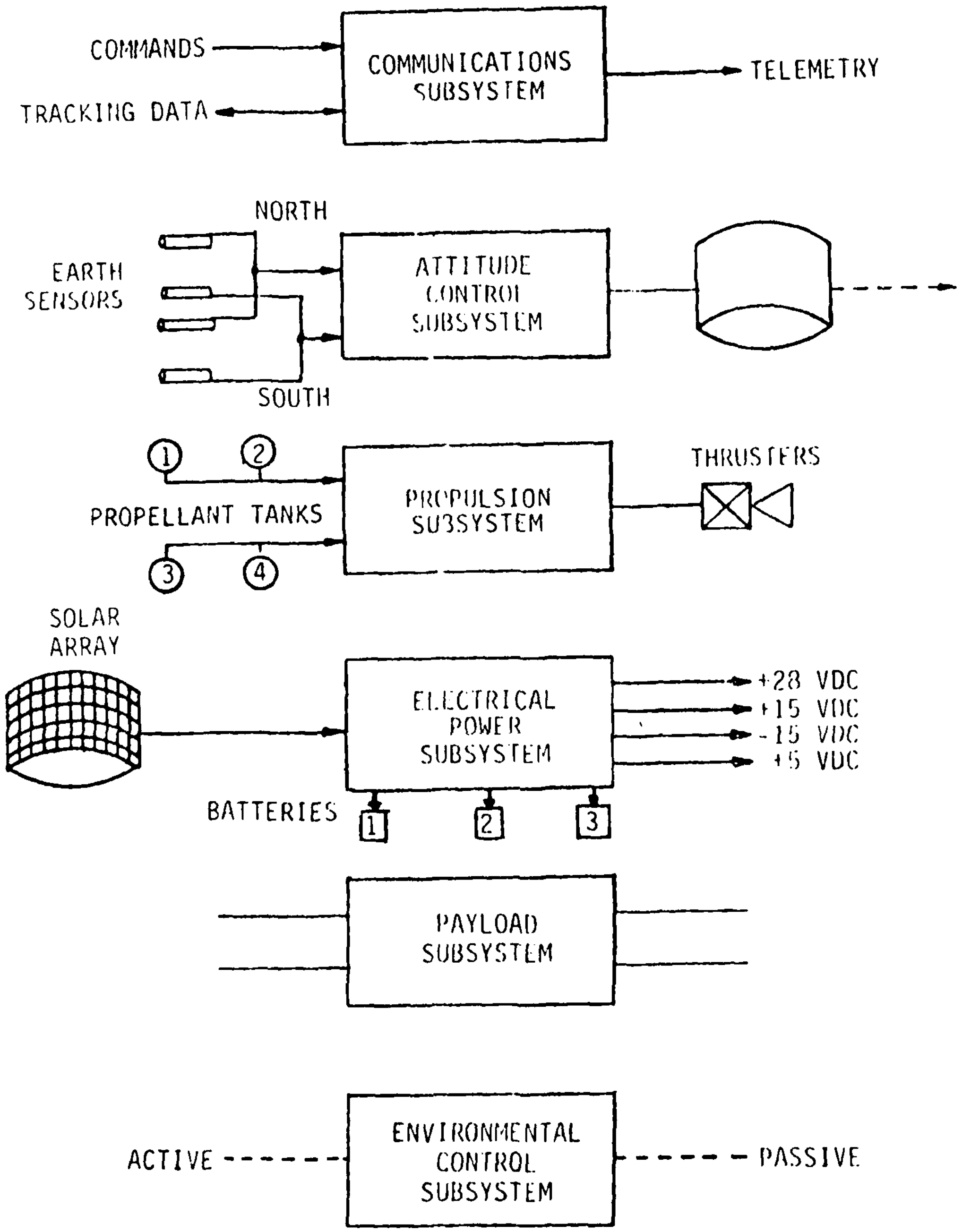
deploy the servicing system may be recouped by the gains in satellite longevity. A similar argument can be made for hardware and ground support costs. Unfortunately, the determination of the critical point is dependent on comprehensive studies which have not been accomplished.

The best choice for the military space policy planner, given such an assessment, is to do the following:

- Follow the NASA OMV program closely to take advantage of potential technology transfusions.
- Design future satellites to be compatible with a projected servicing system. This requires the adoption of and adherence to standard configurations.
- Develop an emergency refueling capability to be demonstrated on a military satellite at the first appropriate contingency.
- Continue to address the launch cost problem.

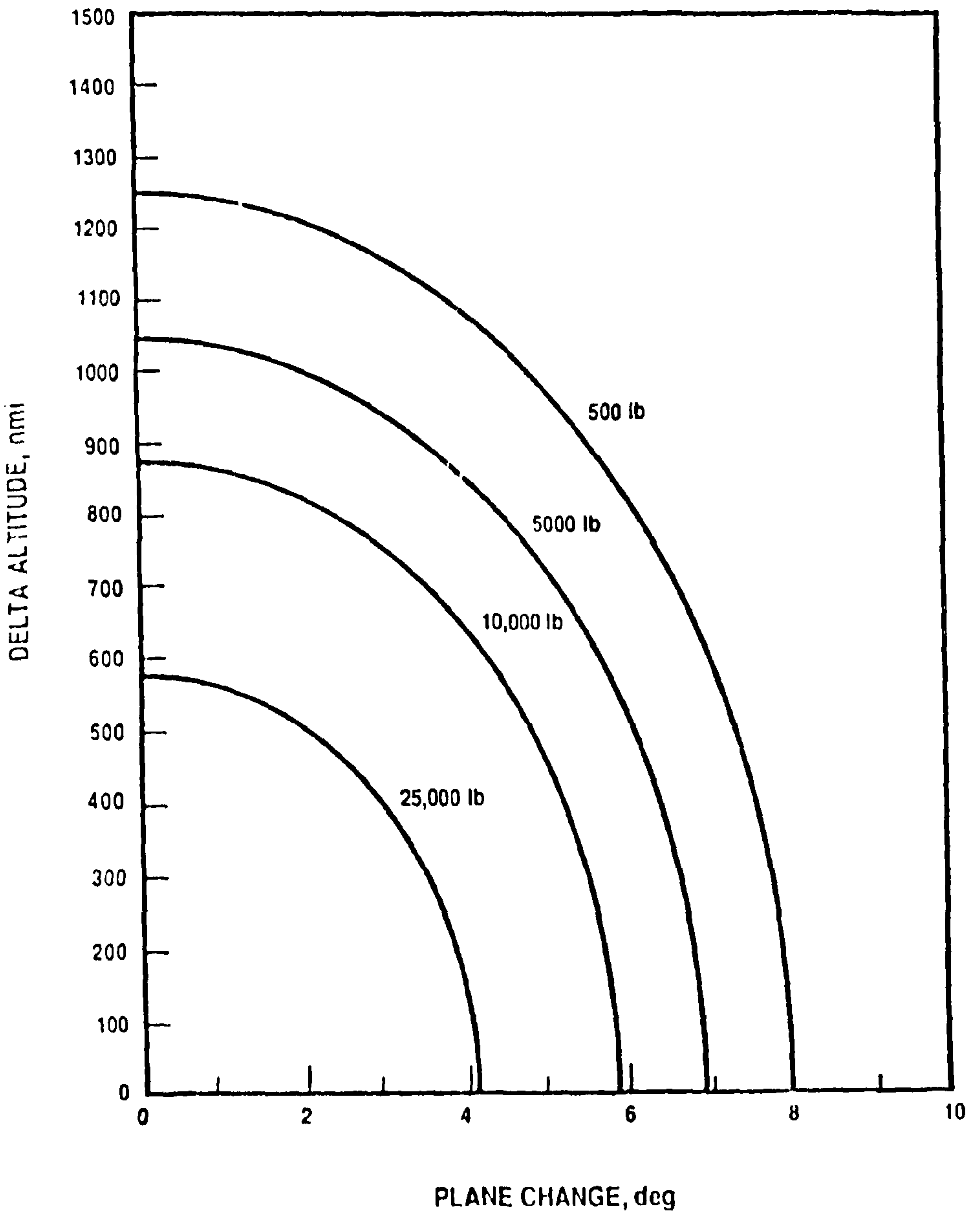
It is likely that the simultaneous pressures to reduce defense spending and to increase reliance on space systems will ultimately force space planners to discover innovative solutions to satisfy mission requirements. As orbital technology and operational experience continues to advance, an evolution toward military orbital logistics

seems inevitable given sufficient reductions in launch costs. Although this study focuses on orbital refueling, the extension of the analytical results to the entire range of orbital servicing functions is logically consistent. The prospect for resultant increases in satellite capability and survivability, combined with the potential for system cost savings, gives on-orbit satellite servicing a highly attractive synergy. Space system policy makers should proceed in preparations for the ultimate integration of the orbital logistics concept as a system-wide military program.



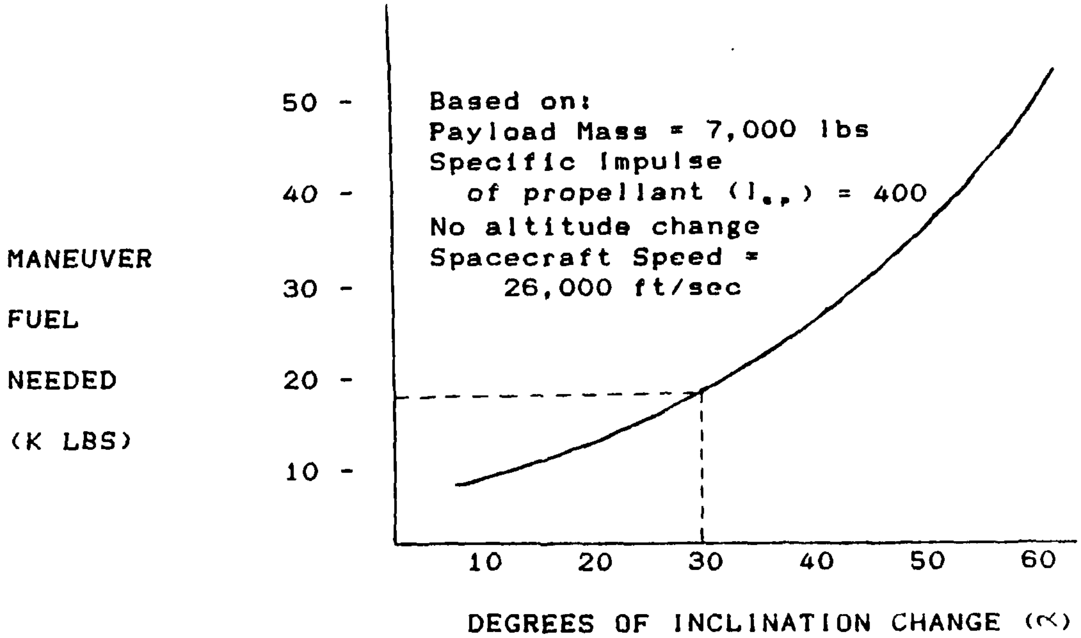
TYPICAL SATELLITE SUBSYSTEMS

FIGURE 1

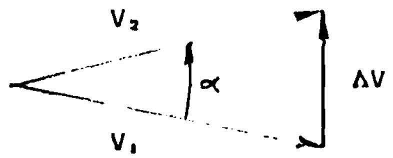


OMV PAYLOAD DEPLOYMENT CAPABILITY FOR ALTITUDE AND PLANE CHANGE (40:14)

FIGURE 2



Mathematical expressions which relate inclination changes to speed, weight, and fuel:



$$V^2 = V_1^2 + V_2^2 - 2V_1V_2 \cos\alpha$$

$$V = \ln \frac{W_1}{W_2} (I_{sp})(g)$$

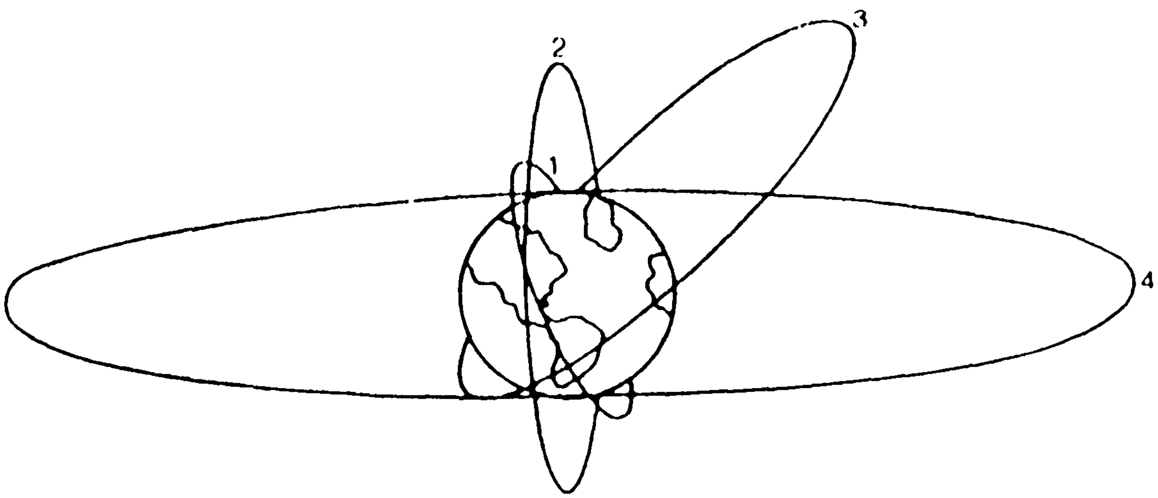
where $\frac{W_1}{W_2} = \frac{\text{Initial Weight}}{\text{Fuel Empty Weight}}$

g = gravitational force

In this example, the 7,000 pound payload would require almost 20,000 pounds of fuel to change its inclination by 30 degrees.

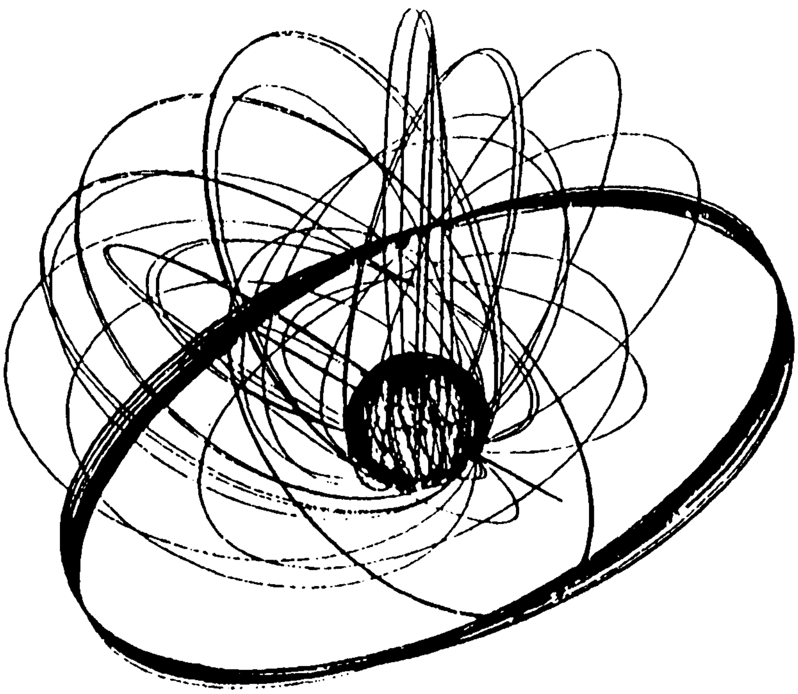
FUEL REQUIREMENTS FOR PLANE CHANGES

FIGURE 3



1. LOW EARTH ORBIT WITH 98-DEGREE SUN-SYNCHRONOUS INCLINATION
2. MEDIUM ALTITUDE SEMI-SYNCHRONOUS ORBIT
3. HIGHLY ELLIPTICAL (MOLNIYA) ORBIT
4. EQUATORIAL GEOSYNCHRONOUS ORBIT

TYPICAL MILITARY ORBITS (25:11)



CONCEPTUAL DISPLAY OF TOTAL MILITARY SYSTEM (32:2)

FIGURE 4

LAUNCH VEHICLE	TYPICAL PAYLOAD	MAXIMUM PAYLOAD WEIGHT (LBS)	LAUNCH COSTS ($M)*
SCOUT	TRANSIT	570	9
DELTA	DMSP	7,600	33
DELTA II	GPS	11,100	38
ATLAS II	DSCS	14,500	60
TITAN 34D	MULTIPLE	27,600	124
TITAN IV	MILSTAR	39,100	142
STS	MULTIPLE	50,000	250 (est.)

*Costs derived from AF/XOXFD Point Paper, 3OCT88.

LAUNCH COSTS FOR VARIOUS PAYLOAD WEIGHTS

FIGURE 5

YEAR -	0	1	2	3	4	5	6	7	8
CASE 1	3xM		3xM		3xM		3xM		
CASE 2	3xM	S		3xM	S		3xM		

<u>Case 1</u>: (no servicer satellites)

- 2 year mean satellite life

- 12 launches at $40M = $ 480M
- 12 satellites at $100M = <u>1200M</u>

$1680M

<u>Case 2</u>: (with servicer satellites)

- 3 year mean satellite life

- 11 launches at $40M = $ 440M
- 9 satellites at $100M = 900M
- 2 servicers at $40M = <u>80M</u>

$1420M

Common Assumptions:

- 3 mission satellites in constellation
- Launches cost $40M each
- Mission satellites cost $100M each (M)
- Servicer satellites cost $40M each (S)
- 8 year program duration
- Ground support costs are equal for each case
- Case 2 servicer available at Year 7 if required

NOTIONAL COST PROFILE COMPARISON

FIGURE 6

GLOSSARY

ASAT	Anti-satellite weapon
C3I	Command, Control, Communications and Intelligence
delta V	Change in velocity vector (inclination or altitude or both)
DMSP	Defense Meteorological Satellite Program
DSCS	Defense Satellite Communications System
EMP	Electro-magnetic Pulse
FLTSATCOM	Fleet Satellite Communications System
GPS	Global Positioning System
MILSTAR	Military Strategic, Tactical and Relay Communications Satellite System
NASA	National Aeronautics and Space Administration
OMV	Orbital Maneuvering Vehicle
OTV	Orbital Transfer Vehicle
SDI	Strategic Defense Initiative
STS	Space Transportation System
TRANSIT	Navy Navigation Satellite System

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